Extremely slow dynamics of Landau-level population during the breakdown of the quantum Hall effect

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Recent experiments have revealed two distinct time scales in the development of the quantum-Hall-effect breakdown (QHEB) at even-integer filling factors. A shorter time scale of a few nanoseconds has been observed in a pulse measurement of the diagonal conductivity [1], while a longer time scale in the region of seconds has been found in AC measurements of the breakdown voltage [2] and the diagonal conductivity [3]. These experiments might suggest the presence of one slow and one fast variables in the QHEB. These two variables could be useful in describing a variety of dynamics of the QHEB in a unified manner. Two models of variables have been proposed in the QHEB. One is the electron heating model which introduces the electron temperature [4-6]. The other is a two-level model [7] which considers the first-excited-Landau-level population (population of N=1). The population of N=0 is determined by the fixed-electron-number condition when the filling factor is two. Both models assume a single variable in the development of the QHEB. In this paper we introduce a two-variable model when the filling factor is two. Two variables we consider are the electron temperature [4-6] and the population of N=1 [7]. The population of N=1, which is equal to the number of holes in N=0, is out of equilibrium when the chemical potential is different between N=0 and N=1 Landau levels. The electron temperature is assumed to be the same in N=0 and N=1 levels, and describes the electron energy distribution within each broadened Landau level. In this paper we study dynamics of these two variables within a thermohydrodynamics [6], and investigate a possibility that these variables describe the slow and fast processes, respectively, observed in the experiments [1-3]. The electron temperature increases due to the Joule heating, which is proportional to the diagonal conductivity and therefore enhanced at the QHEB. The time scale of the electron temperature is the resistance (for the heat flow to the lattice) multiplied by the electronic heat capacity, and is estimated to be of the order of 1-10 nanoseconds, depending on the density of states at the Fermi level. The nonequilibrium population of N=1 will relax through (1) quasielastic inter-Landau-level scatterings (QUILLS) [8], (2) scatterings between edge and bulk states, and (3) transfer at electrical contacts. If we consider a narrow Corbino device with a narrow Landau level broadening, the electron transfer through source and drain contacts is most important. In this case, the dynamics of the N=1 population is determined by diffusion through extended states within each Landau level to either contact, and is slow when the thermal activation to extended states is not fully developed in the early stage of the QHEB. The order-of-magnitude estimate of the time scale for the N=1 population is calculated to be 0.1-10 seconds depending on the lattice temperature. We also find an avalanche-like feature in the calculated temporal evolution of the N=1 population, which could be useful in judging the validity of the present model if the corresponding observed result becomes available. [1] B. E. Saol, G. Nachtwei, K. von Klitzing, G. Hein, and K. Eberl, Phys. Rev. B 66, 075305 (2002). [2] N. G. Kalugin, B. E. Saol, A. Bu, A. Hirsch, C. Stellmach, G. Hein, and G. Nachtwei, Phys. Rev. B 68, 125313 (2003). [3] A. Buss, F. Hohls, F. Schulze-Wischeler, C. Stellmach, G. Hein, R. J. Haug, and G. Nachtwei, Phys. Rev. B 71,195319 (2005). [4] G. Ebert, K. von Klitzing, K. Ploog, and G. Weimann, J. Phys. C. 16 (1983) 5441. [5] S. Komiyama, T. Takamasu, S. Hiyamizu, and S. Sasa, Solid State Commun. 54 (1985) 479. [6] H. Akera and H. Suzuura, J. Phys. Soc. Jpn. 74, 997 (2005). [7] K. Gven, R. R. Gerhardts, I. I. Kaya, B. E. Saol, and G. Nachtwei, Phys. Rev. B 65, 155316 (2002). [8] L. Eaves and F.W. Sheard, Semicond. Sci. Technol. 1 (1986) 346.